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MODIFICATION OF THE BACKGROUND FLOW BY ROLL VORTICES

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Use of observed wind profiles, such as those obtained from ascent or descent aircraft soundings, for the identification of the expected roll modes is hindered by the fact that these modes are able to modify the wind profiles. When such modified wind profiles are utilized to estimate the critical values of the dynamic and thermodynamic forcing rates, large errors in the preferred orientation angles and aspect ratios of the rolls may result. Nonlinear analysis of a 14-coefficient spectral model of roll circulations shows that the primary modification of the background wind is the addition of a linear component. When the linear profile having the correct amount of shear is subtracted from the observed cross-roll winds, then the pre-roll wind profile can be estimated. In this paper, a preliminary test of this hypothesis is given for a case in which cloud streets were observed during FIRE.

The amount of error in the expected orientation angle that is introduced by using the roll-modified winds as the basic state can be illustrated using the Ekman wind profile. A typical Ekman cross-roll profile U_P is given in Fig. 1a. The geostrophic wind is from the west and the Ekman wind direction is also from the west when $z = \pi D$, where $D = 115$ m is the Ekman depth; because the model contains a right-handed coordinate system in which the roll axis is parallel to the y-direction, southerly winds have negative values. An inflection point mode may develop from this wind profile. It has a preferred orientation angle of 5° to the right of the geostrophic wind, or 275°, while the preferred aspect ratio $a = 2z_T/L$ is 0.7; here $z_T = 600$ m is the domain height, so the expected roll spacing L is approximately 1700 m. The 14-coefficient model is integrated for these values of orientation angle and aspect ratio and for a set of supercritical values of the dynamic forcing rates, given by a Reynolds number $Re = |\underset{\sim}{V}(z_T)|z_T/(\pi\nu)$, and the thermodynamic forcing rates, given by the Rayleigh number $Ra = gz_T^3\Delta_zT/(\nu\kappa T_{00}\pi^4)$; here $|\underset{\sim}{V}(z_T)|$ is the wind at the domain top, ν and κ are the eddy viscosity and thermometric conductivity respectively, and Δ_zT is a combined measure of the sea surface/air temperature difference and the environmental lapse rate of potential temperature. For this example, the critical values are $Re_c = 91$ and $Ra_c = 0$, and the forcing rates $Re = 100$ and $Ra = 100$ are used in the integration. The linear cross-wind profile U_L created in this case is shown in Fig. 1b. After this linear profile is added to the original Ekman one, the low-level wind speed increases, as does the shear near the inflection point (Fig. 1c). Use of this modified profile U_M in the stability analysis produces an orientation angle for the inflection point mode that is 15° further to the right of the geostrophic wind than the angle produced by the original Ekman profile. However, the preferred aspect ratio does not vary considerably. For this example, therefore, the primary consequences of using the wrong basic wind profile are a large error in the expected orientation angle of the rolls and an overestimate of the cross-roll shear in the basic state winds.

Cloud streets in relatively clear air were observed in the western half of the Landsat scene on July 7, 1987. A descent sounding measured on Flight 5 of the Electra between 2136 and 2137:30 UTC was used to provide the observed wind and temperature profiles for the analysis (Figs. 2a, 3b). Moisture measurements, lidar data, and flight video tapes were used to provide an estimate of the domain height $z_T = 450$ m, and the layer mean wind direction of 340°

gave an estimate of the observed roll orientation; this orientation agrees well with that found on the Landsat image provided us by Dr. Robert F. Cahalan. When the observed wind profile is used in the stability analysis, an orientation 35° to the right of the mean wind direction, or 15° (slightly east of north), is obtained for the thermal mode. This is the only likely mode since the cross-roll profile does not have an inflection point (Fig. 2a), and, as calculated by Dr. Bruce A. Albrecht, the sea surface temperature exceeded the surface air temperature by approximately 0.5 °C. Clearly 35° is an unacceptably large error in the orientation angle. Thus the next task is to find the linear cross-roll wind profile U_L that must be removed from the one in Fig. 2a in order that the resulting profile produces the correct orientation angle $\beta = 0°$. A range of slopes is considered, and the effects on the preferred orientation angle β_p given by the stability analysis are shown in Fig. 2b. Because the orientation angle varies monotonically with changes in the slope m of the removed profile, the hypothesized roll contribution is easy to identify. The linear cross-roll profile whose removal gives 0° as the preferred roll orientation is displayed in Fig. 2c. A total wind speed variation of 1.6 m/s is estimated to have been produced by the rolls. The estimated pre-roll basic wind profile U_P that gives the correct orientation angle is shown in Fig. 2d; note its quadratic form that is often associated with thermally forced roll circulations.

The above method for estimating the roll contribution to the background wind profile is acceptable only if integration of the model for reasonable values of the parameters produces the necessary wind modification U_L. The results of this test are given in Fig. 3. In Fig. 3a the transition curves are shown, together with an estimate of the forcing values characterizing the atmosphere. The dashed line shows the transition curve for the thermal mode when the observed profile U_M in Fig. 2a is used, while the solid line shows the curve when the estimated pre-roll profile U_P in Fig. 2d is used. A few of the preferred orientation angles β_p and aspect ratios a_p are given for both curves; note that when the assumed roll modification is removed from the observed wind profile, the orientation angle is much improved and the aspect ratio is increased, implying that the expected roll spacing is decreased. The quadrilateral encloses the parameter region corresponding to that for the atmosphere. A sea surface/air temperature difference ranging between 0.2 °C and 0.8 °C, a lapse rate of 9.5 °C/km characterizing the lower portion of the temperature profile in Fig. 3b, and eddy viscosity and thermometric conductivity variations between 10 m^2/s and 50 m^2/s were used to produce the vertices of the quadrilateral; these vertices are (Ra,Re) = (0,45); (10,45); (0,190); (125,190). It is reassuring that the transition curves pass through the left side of the quadrilateral, implying that rolls supporting the cloud streets were generated by the thermal mode. The star in Fig. 3a shows the values of Ra and Re used to integrate the model. Because this point is well beyond the critical values given by the solid curve, a range of aspect ratios may be used in the integration; if too large an aspect ratio is chosen, then a temporally complicated roll solution results. However, when an aspect ratio of 0.9 is picked, which implies that the atmosphere evolved along a path roughly paralleling the right edge of the quadrilateral, then a nonlinear solution representing a propagating roll having a steady amplitude results. This solution is shown in Fig. 3c, and it produces the cross-roll wind profile modification shown in Fig. 3d. Clearly, this roll produces the necessary modification that is given in Fig. 2c, indicating that the amount of shear removed to estimate the pre-roll profile in Fig. 2d is plausible. This roll mode propagates from right to left at the rate 0.3 m/s, as might be expected in these coordinates because the pre-roll winds are mostly negative and of this magnitude in Fig. 2d. Moreover, the maximum speeds in the updraft are 0.8 m/s. Finally, the roll spacing of approximately 1 km is also reasonable, as indicated by inspection of the Landsat image. Thus by removing the contribution of the roll circulations to the measured wind profile, a pre-roll basic state wind profile is found that gives a reasonable roll mode. Further tests of this approach are planned with other wind profiles measured during FIRE.

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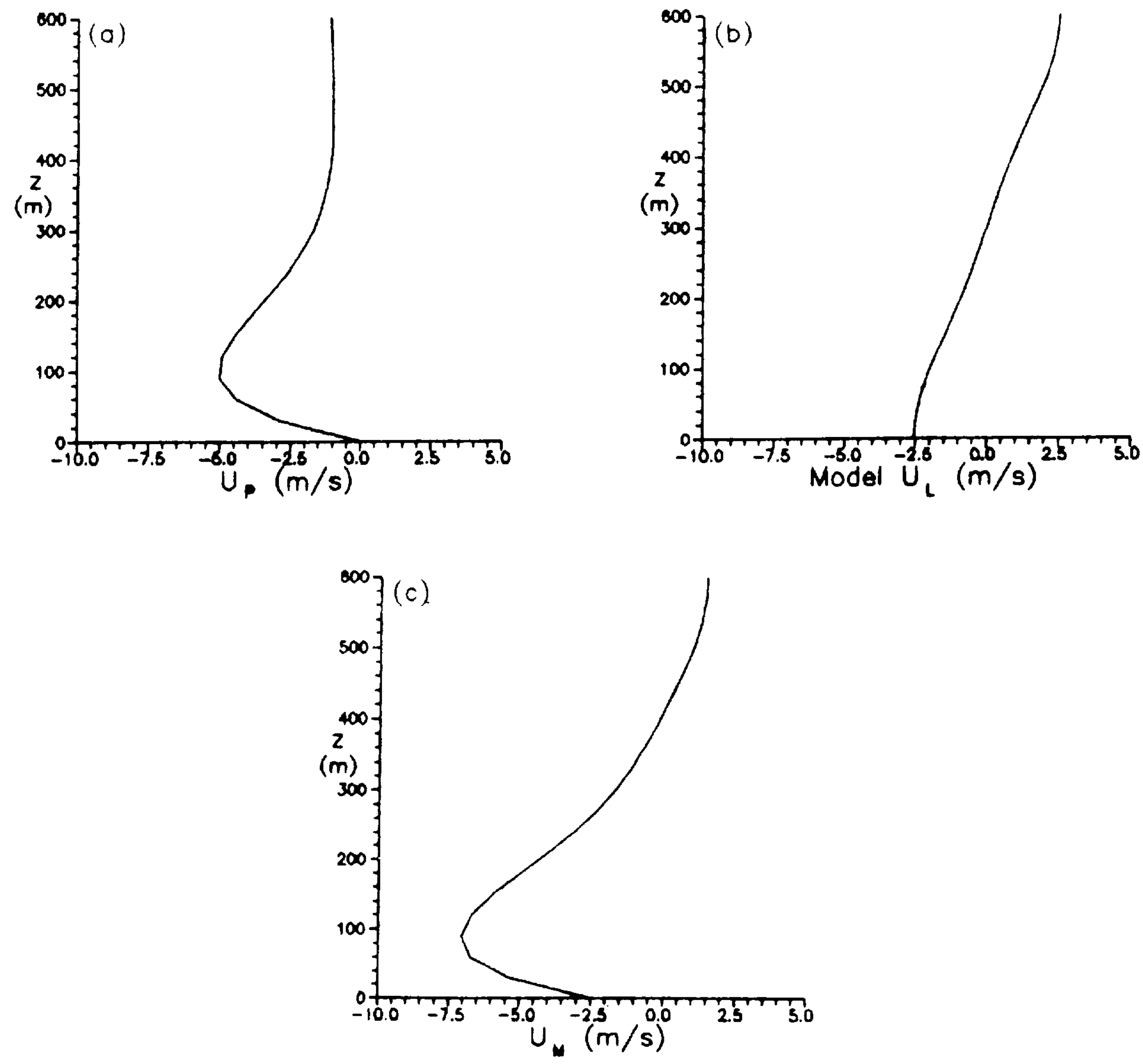

Figure 1. Ekman profile with a westerly geostrophic wind that is used to illustrate how much the orientation angle β may change when a roll-modified wind profile is used in the stability analysis. Here $\nu = \kappa = 25\ m^2/s$ and $z_T = 600$ m. In (a) the original cross-roll profile U_P is given for an Ekman depth D =115 m and a roll, or y-axis, orientation of 275°; the negative values correspond therefore to southerly winds. In (b) the linear modification U_L of the cross-roll winds by the rolls is shown when Re = 100, or Re - Re_c = 9, and Ra = 100, or Ra - Ra_c = 100. In (c) the total modified cross-roll profile U_M is given.

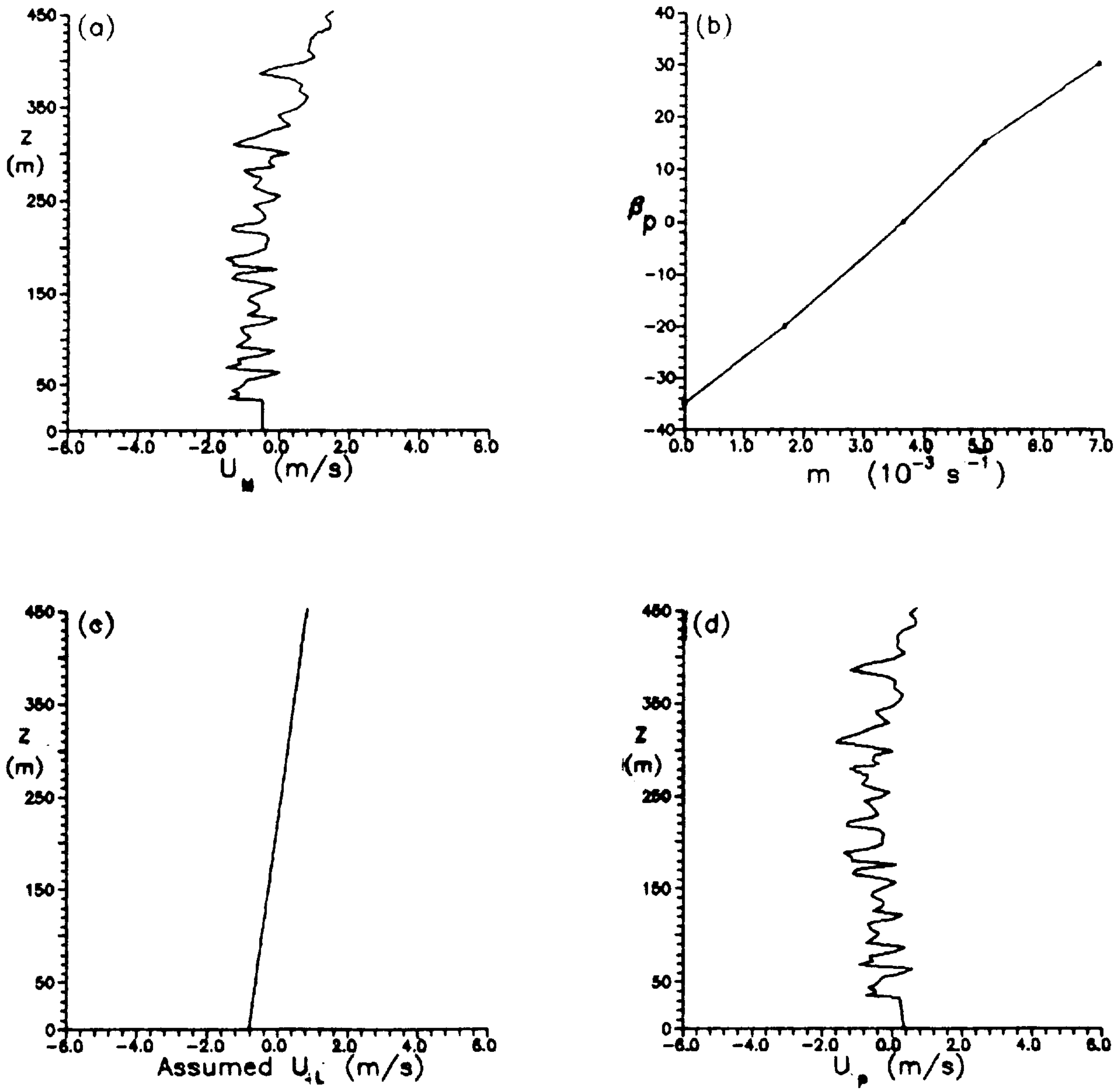

Figure 2. Cross-roll wind profiles for the descent sounding measured by the NCAR Electra in the predominantly clear air on July 7, 1987 (Flight 5) between 2136 and 2137:30 UTC; the cross-roll, or x-, direction is 70° (~ENE), so that negative values correspond to winds having directions less than 340°. In (a) the measured profile U_M is given, with the wind speed from the lowest level extrapolated to the surface. In (b) is shown the preferred orientation angle β_p relative to the mean wind direction (positive values to the left, negative values to the right) that is given by the stability analysis, as a function of the slope m in the cross-roll linear wind profile $U_L = mz + b$ that is removed from the one in (a). In (c) the optimal linear profile U_L is shown that gives an orientation angle $\beta_p = 0°$. In (d) the estimated pre-roll profile U_P is given that is found by subtracting the profile in (c) from the one in (a).

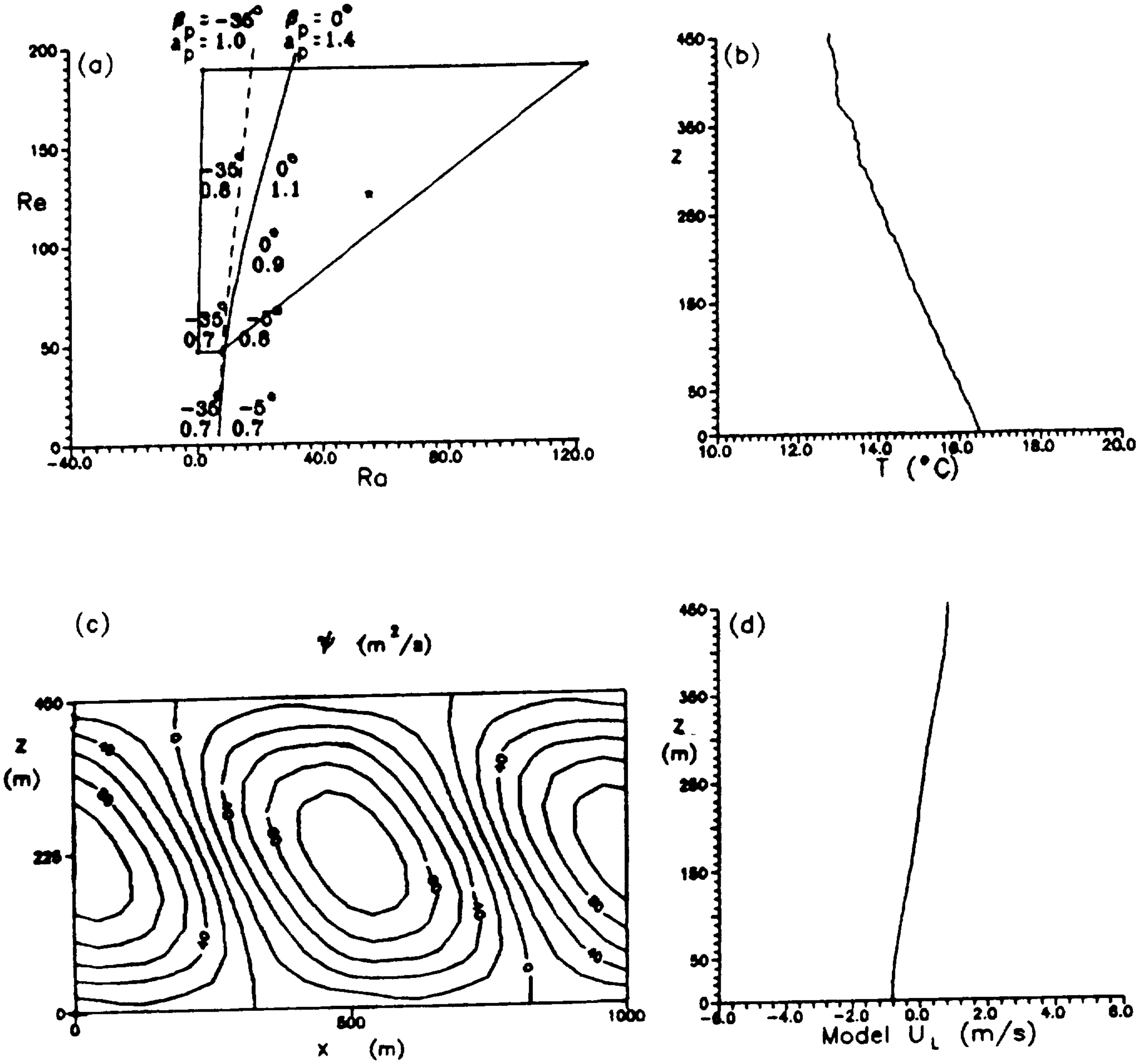

Figure 3. Results from the 14-coefficient spectral model. In (a) the dashed line denotes the transition curve obtained when the measured wind profile in Fig. 2a is used, the solid line denotes the transition curve obtained when the estimated pre-roll wind profile in Fig. 2d is used, the numbers next to the curves denote the preferred orientation angle β_p and aspect ratio a_p, the quadrilateral encloses the parameter values for the atmosphere, and the star denotes the parameter values used in the model integration. In (b) the observed temperature profile from the descent sounding of Fig. 2a is shown; the lapse rate in the lower part of the sounding is combined with an estimate of the sea surface/air temperature difference to calculate values of Ra for the quadrilateral in (a). In (c) and (d) the nonlinear solution to the 14-coefficient model is shown for Ra = 55, Re = 125, $\beta = 0°$, a = 0.9 and the estimated pre-roll wind profile given in Fig. 2d; in (c) the roll circulation, which propagates at a steady rate of 0.3 m/s from right to left, is shown and in (d) the calculated roll-produced modification U_L of the wind profile is shown.